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(54) **CEMENT TESTING**

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4,377,087 A	3/1983	Rodot
4,389,896 A	6/1983	Babcock
4,408,489 A	10/1983	Spangle
4,430,889 A	2/1984	Sutton
4,487,056 A	12/1984	Wiley
4,491,017 A	1/1985	Iyer
4,538,452 A	9/1985	Hrvojic
4,567,759 A	2/1986	Ekstrom et al.
4,567,765 A	2/1986	Rao et al.
4,607,530 A	8/1986	Chow
4,648,264 A	3/1987	Freese et al.
4,685,092 A	8/1987	Dumont
4,691,558 A	9/1987	Vinson et al.

(Continued)

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#### FOREIGN PATENT DOCUMENTS

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DE	86 01 833	1/1987
EP	0 124 383 A1	11/1984

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(Continued)

#### OTHER PUBLICATIONS

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Gary Funkhouser et al., "Measuring Cement Properties" U.S. Appl.  
No. 11/622,255, filed Jan. 11, 2007 (25 pages).

(Continued)

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USPC ..... **73/37; 73/788; 73/38**

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See application file for complete search history.

(56) **References Cited**

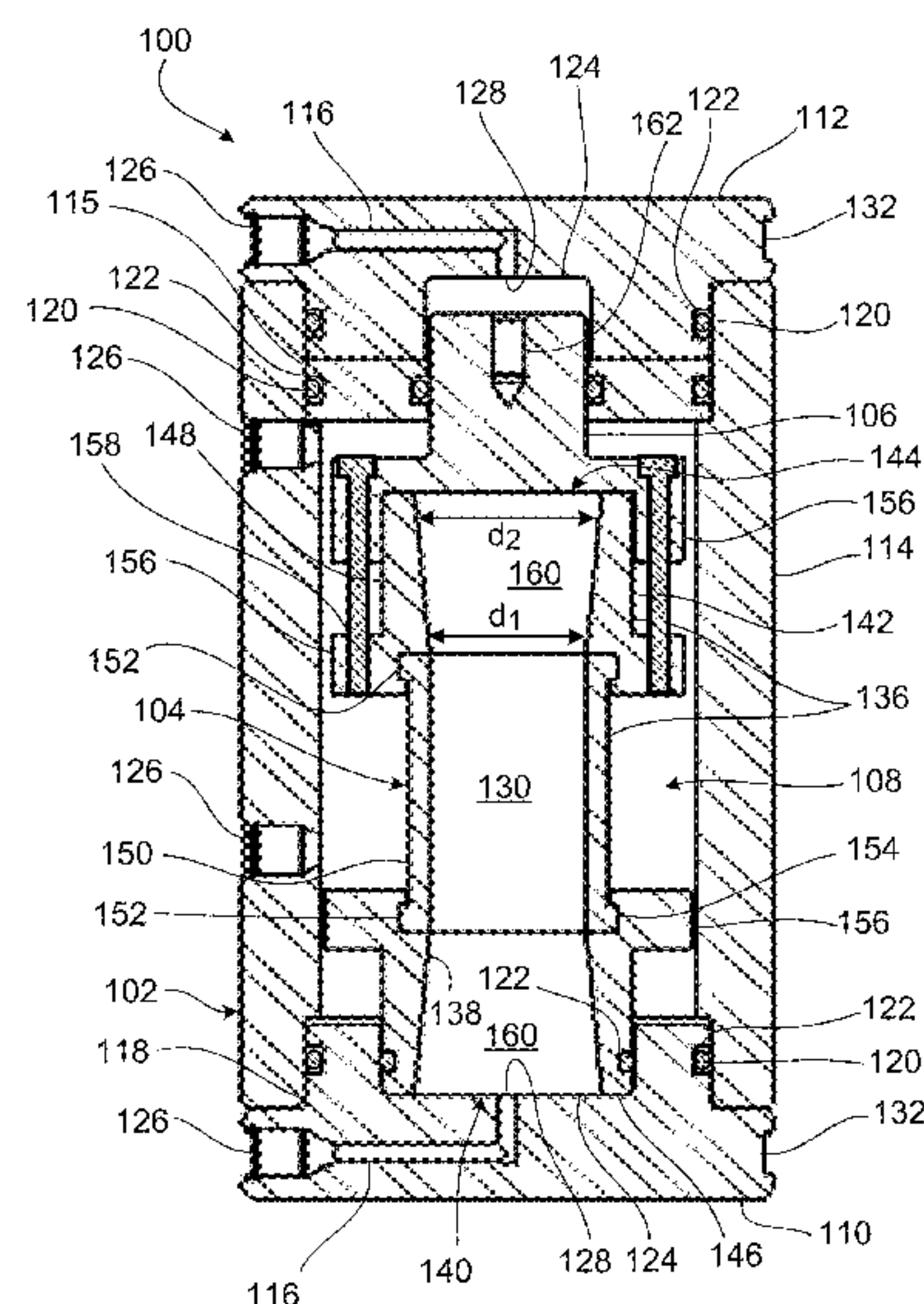
#### U.S. PATENT DOCUMENTS

2,662,827 A	12/1953	Clark
3,541,845 A	11/1970	Kierkegaard-Hansen
3,574,281 A	4/1971	Casey et al.
3,619,463 A	11/1971	Budin et al.
3,779,085 A	12/1973	Rice
4,138,892 A	2/1979	Davis
4,182,191 A	1/1980	Ikeda
4,259,868 A	4/1981	Rao et al.

(57) **ABSTRACT**

Devices and methods for testing cement include: a pressure vessel with a sample container inside an interior working volume of the pressure vessel, the pressure vessel configured to supply a first pressurized fluid to control a pore pressure of a cement sample and to supply a second pressurized fluid to lateral exterior surfaces of the sample container to provide a confining pressure that can be different than the pore pressure.

**13 Claims, 7 Drawing Sheets**





(56)

## References Cited

## U.S. PATENT DOCUMENTS

4,703,427	A	10/1987	Catala et al.	6,547,871	B2	4/2003	Chatterji et al.
4,757,479	A	7/1988	Masson et al.	6,554,071	B1	4/2003	Reddy et al.
4,809,237	A	2/1989	Vogel et al.	6,591,910	B1	7/2003	Chatterji et al.
4,823,594	A	4/1989	Gray	6,595,068	B2	7/2003	Brovold et al.
4,848,145	A	7/1989	Blaschke et al.	6,610,139	B2	8/2003	Reddy et al.
4,893,285	A	1/1990	Masson et al.	6,644,402	B1	11/2003	Sharma et al.
4,896,303	A	1/1990	Leslie et al.	6,655,213	B1	12/2003	Reinhardt et al.
4,970,695	A	11/1990	Huau	6,660,080	B2	12/2003	Reddy et al.
5,009,512	A	4/1991	Lessi et al.	6,711,941	B2	3/2004	Braithwaite et al.
5,036,709	A	8/1991	McRae	6,762,156	B2	7/2004	Heathman et al.
5,089,989	A	2/1992	Schmidt et al.	6,767,867	B2	7/2004	Chatterji et al.
5,127,473	A	7/1992	Harris et al.	6,782,735	B2	8/2004	Walters et al.
5,159,828	A	11/1992	Steiger et al.	6,789,621	B2	9/2004	Wetzel et al.
5,216,638	A	6/1993	Wright	6,797,054	B2	9/2004	Chatterji et al.
5,226,310	A	7/1993	Steiger	6,817,238	B2	11/2004	Go Boncan et al.
5,233,863	A	8/1993	Surjaatmadja et al.	6,818,596	B1	11/2004	Hayes
5,248,200	A	9/1993	Walsh	6,828,922	B1	12/2004	Gremmert et al.
5,325,723	A	7/1994	Meadows et al.	6,829,922	B2	12/2004	Patin et al.
5,346,012	A	9/1994	Heathman et al.	6,834,233	B2	12/2004	Economides et al.
5,353,637	A	10/1994	Plumb et al.	6,843,846	B2	1/2005	Chatterji et al.
5,368,103	A	11/1994	Heathman et al.	6,874,353	B2	4/2005	Johnson et al.
5,377,160	A	12/1994	Tello et al.	6,892,814	B2	5/2005	Heathman et al.
5,377,753	A	1/1995	Haberman et al.	6,910,535	B2	6/2005	Tare et al.
5,389,706	A	2/1995	Heathman et al.	6,918,292	B2	7/2005	Go Boncan et al.
5,412,990	A	5/1995	D'Angelo et al.	6,951,249	B1	10/2005	Chatterji et al.
5,487,307	A	1/1996	Landgren et al.	6,964,302	B2	11/2005	Luke et al.
5,488,994	A	2/1996	Laurel et al.	6,978,835	B1	12/2005	Reddy et al.
5,544,704	A	8/1996	Laurel et al.	6,994,164	B2	2/2006	Tare et al.
5,571,951	A	11/1996	Jamth	7,004,256	B1	2/2006	Chatterji et al.
5,572,021	A	11/1996	Heathman et al.	7,008,477	B2	3/2006	Chatterji et al.
5,696,059	A	12/1997	Onan et al.	7,013,975	B2	3/2006	Chatterji et al.
5,712,431	A	1/1998	Vilendrer	7,048,054	B2	5/2006	Heathman et al.
5,718,292	A	2/1998	Heathman et al.	7,089,816	B2	8/2006	Hakimuddin
5,741,971	A	4/1998	Lacy	7,096,944	B2	8/2006	Vargo, Jr. et al.
5,763,773	A	6/1998	Birchak et al.	7,128,142	B2	10/2006	Heathman et al.
5,783,822	A	7/1998	Buchanan et al.	7,128,149	B2	10/2006	Heathman et al.
5,787,983	A	8/1998	Heathman et al.	7,143,827	B2	12/2006	Chatterji et al.
5,836,200	A	11/1998	Belonenko et al.	7,178,590	B2	2/2007	Vargo, Jr. et al.
5,869,750	A	2/1999	Onan et al.	7,191,663	B2	3/2007	Go Boncan et al.
5,964,293	A	10/1999	Chatterji et al.	7,222,676	B2	5/2007	Patel et al.
5,968,255	A	10/1999	Mehta et al.	7,240,545	B1	7/2007	Jennings
5,969,059	A	10/1999	Murai et al.	7,244,303	B2	7/2007	Chatterji et al.
5,972,103	A	10/1999	Mehta et al.	7,255,170	B2	8/2007	Chatterji et al.
5,992,223	A	11/1999	Sabins et al.	7,284,898	B2	10/2007	Duell et al.
5,996,693	A	12/1999	Heathman	7,285,166	B2	10/2007	Luke et al.
6,019,835	A	2/2000	Chatterji et al.	7,296,927	B2	11/2007	Reddy et al.
6,053,245	A	4/2000	Haberman	7,325,629	B2	2/2008	Blaschke et al.
6,055,874	A	5/2000	Onan et al.	7,373,982	B2	5/2008	Brothers et al.
6,060,434	A	5/2000	Sweatman et al.	7,380,466	B2	6/2008	Deeg
6,070,662	A	6/2000	Ciglenec et al.	7,549,320	B2	6/2009	Funkhouser et al.
6,112,599	A	9/2000	Maki, Jr.	2001/0001381	A1	5/2001	Reddy et al.
6,124,246	A	9/2000	Heathman et al.	2001/0037687	A1	11/2001	Brovold
6,134,954	A	10/2000	Suresh et al.	2003/0140707	A1	7/2003	Pyle et al.
H1932	H	1/2001	Heathman et al.	2003/0150263	A1	8/2003	Economides et al.
6,170,575	B1	1/2001	Reddy et al.	2003/0161211	A1	8/2003	Duell et al.
6,209,646	B1	4/2001	Reddy et al.	2003/0221829	A1	12/2003	Patel et al.
6,227,039	B1	5/2001	Te'eni	2004/0054262	A1	3/2004	Horak
6,227,294	B1	5/2001	Chatterji et al.	2004/0055392	A1	3/2004	Patin et al.
6,245,142	B1	6/2001	Reddy et al.	2004/0154263	A1	8/2004	Li et al.
6,258,757	B1	7/2001	Sweatman et al.	2004/0221990	A1	11/2004	Heathman et al.
6,269,684	B1	8/2001	Maki, Jr. et al.	2004/0226483	A1	11/2004	Chatterji et al.
6,270,565	B1	8/2001	Heathman	2005/0009710	A1	1/2005	Heathman et al.
6,345,535	B1	2/2002	Sabins et al.	2005/0080161	A1	4/2005	Tare et al.
6,367,549	B1	4/2002	Chatterji et al.	2005/0109507	A1	5/2005	Heathman et al.
6,367,550	B1	4/2002	Chatterji et al.	2005/0126300	A1	6/2005	Go Boncan et al.
6,379,456	B1	4/2002	Heathman et al.	2005/0135185	A1	6/2005	Duell et al.
6,444,316	B1	9/2002	Reddy et al.	2005/0152432	A1	7/2005	Hakimuddin
6,454,001	B1	9/2002	Thompson et al.	2005/0204960	A1	9/2005	Heathman et al.
6,478,868	B1	11/2002	Reddy et al.	2006/0000612	A1	1/2006	Reddy et al.
6,478,869	B2	11/2002	Reddy et al.	2006/0225523	A1	10/2006	Reddy et al.
6,484,568	B1	11/2002	Griffith et al.	2006/0258545	A1	11/2006	Chatterji et al.
6,494,951	B1	12/2002	Reddy et al.	2007/0012441	A1	1/2007	Heathman et al.
6,510,743	B2	1/2003	McAfee et al.	2007/0082822	A1	4/2007	Kirsner et al.
6,527,051	B1	3/2003	Reddy et al.	2007/0105995	A1	5/2007	Chatterji et al.
6,527,438	B2	3/2003	Zollinger et al.	2007/0169937	A1	7/2007	Allin et al.
				2007/0173412	A1	7/2007	Allin et al.
				2008/0168848	A1	7/2008	Funkhouser et al.
				2008/0178683	A1	7/2008	Heathman et al.



(56)

**References Cited****U.S. PATENT DOCUMENTS**

2008/0197605 A1 8/2008 Blaschke et al.  
 2009/0084189 A1\* 4/2009 McMechan et al. .... 73/803  
 2011/0061525 A1\* 3/2011 Gray et al. .... 92/75

**FOREIGN PATENT DOCUMENTS**

EP 0 176 400 B1 4/1986  
 EP 0 101 580 B1 12/1986  
 EP 0 110 750 B1 9/1988  
 EP 0 098 778 B1 3/1989  
 EP 0 198 985 B1 12/1989  
 EP 0 443 936 A1 8/1991  
 EP 0 395 499 B1 7/1993  
 EP 0 176 408 B1 4/1996  
 EP 0 865 612 B1 6/2002  
 EP 1 541 987 6/2005  
 FR 2 340 551 9/1977  
 GB 2 353 546 A 2/2001  
 GB 2 354 026 A 3/2001  
 GB 2 355 742 A 5/2001  
 GB 2 386 625 A 9/2003  
 WO WO 00/49273 8/2000  
 WO WO 2004/008302 A1 10/2004  
 WO WO 2005/065411 7/2005

**OTHER PUBLICATIONS**

Wolfgang F. J. Deeg, "Apparatus and Method for Determining Mechanical Properties of Cement for a Well Bore" U.S. Appl. No. 11/206,719, filed Aug. 18, 2005 (32 pages).  
 David Leon Meadows et al., "Cement Testing" U.S. Appl. No. 13/542,011, filed Jul. 5, 2012 (31 pages).  
 David Leon Meadows et al., "Cement Testing" U.S. Appl. No. 13/409,745, filed Mar. 1, 2012 (43 pages).  
 Authorized officer Athina Nickitas-Etienne, International Preliminary Report on Patentability in International Application No. PCT/GB2010/002001, mailed Dec. 6, 2012, 7 pages.  
 Authorized officer Peter Thomte, International Search Report and Written Opinion in International Application No. PCT/GB2010/002001, mailed Nov. 19, 2012, 10 pages.

"Standard Test Method for Tensile Strength of Hydraulic Cement Mortars", ASTM Standards, C-190-85, (No Month, 1985) pp. 197-202.

Clayton, N. et al., "The Diphasic Concept, With Particular Reference to Concrete", *Developments in Concrete Technology*, vol. 1, F. D. Lydon, Ed.; Applied Science Publisher Ltd, Chapter 7, pp. 283-318, (1979).

Clayton, N., "Fluid-pressure Testing of Concrete Cylinders," *Magazine of Concrete Research*, vol. 30, No. 102, (Mar. 1978), pp. 26-30.

Deeg, Wolfgang, et al., "How Foamed Cement Advantages Extend to Hydraulic Fracturing Operations," *World Oil*, Nov. 1999, pp. 51-53.

Dillenbeck, R.L., GoBoncan, V., and Rogers, M.J., "Testing Cement Static Tensile Behavior Under Downhole Conditions," SPE 97967, Society of Petroleum Engineers, Copyright 2005, 12 pages.

FlexiForce®, materials downloaded from Tekscan website (www.tekscan.com) on FlexiForce® sensors), <http://www.tekscan.com/flexiforce.html>, visited Aug. 3, 2005, 20 pages.

Goodwin, K.J., "Cement Sheath Stress Failure," SPE Drilling Engineering, SPE 20453, Dec. 1992, pp. 291-296, and additional pp. 501-508 from SPE 20453.

Love, A.E.H., "A Treatise on the Mathematical Theory of Elasticity," Fourth Edition, Dover Publications, New York, 1944, pp. 144-145.

Mindess, S. et al., "The Nitrogen Gas Tension Test of Concrete", Proceedings of ConMat '05 and Mindess Symposium, Aug. 22-24, 2005, The University of British Columbia, Vancouver, Canada, 8 pages, (2005).

Minear, John W. and Goodwin, K. Joe, "Cement-Sheath Evaluation," Chapter 10, Petroleum Well Construction, John Wiley & Sons Publisher, ISBN 0-471-96938-9, copyright 1998, front and back cover and pp. 271-296.

Richart, Frank E. et al., "A Study of the Failure of Concrete Under Combined Compressive Stresses", The University of Illinois—Engineering Experiment Station, Bulletin No. 185, (Nov. 1928) pp. 3-253.

Sabins, Fred, "MMS Project Long-Term Integrity of Deepwater Cement Systems Under Stress/Compaction Conditions", CSI Technologies, Sep. 3, 2004.

Thiercelin, J.J., et al., "Cement Design Based on Cement Mechanical Response," SPE Drilling & Completion, Society of Petroleum Engineers, SPE 52890, Dec. 1998, pp. 266-273.

\* cited by examiner

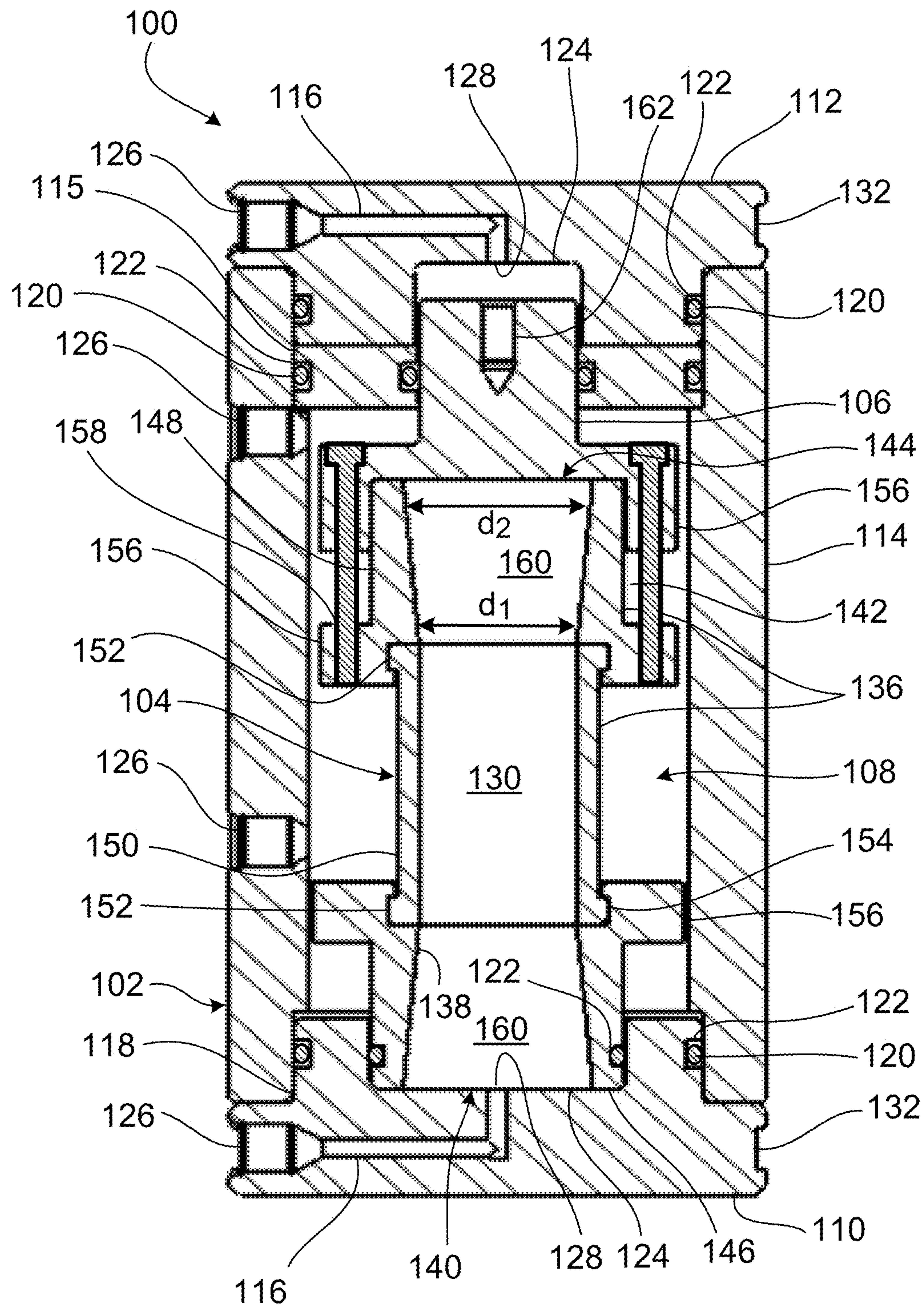


FIG. 1



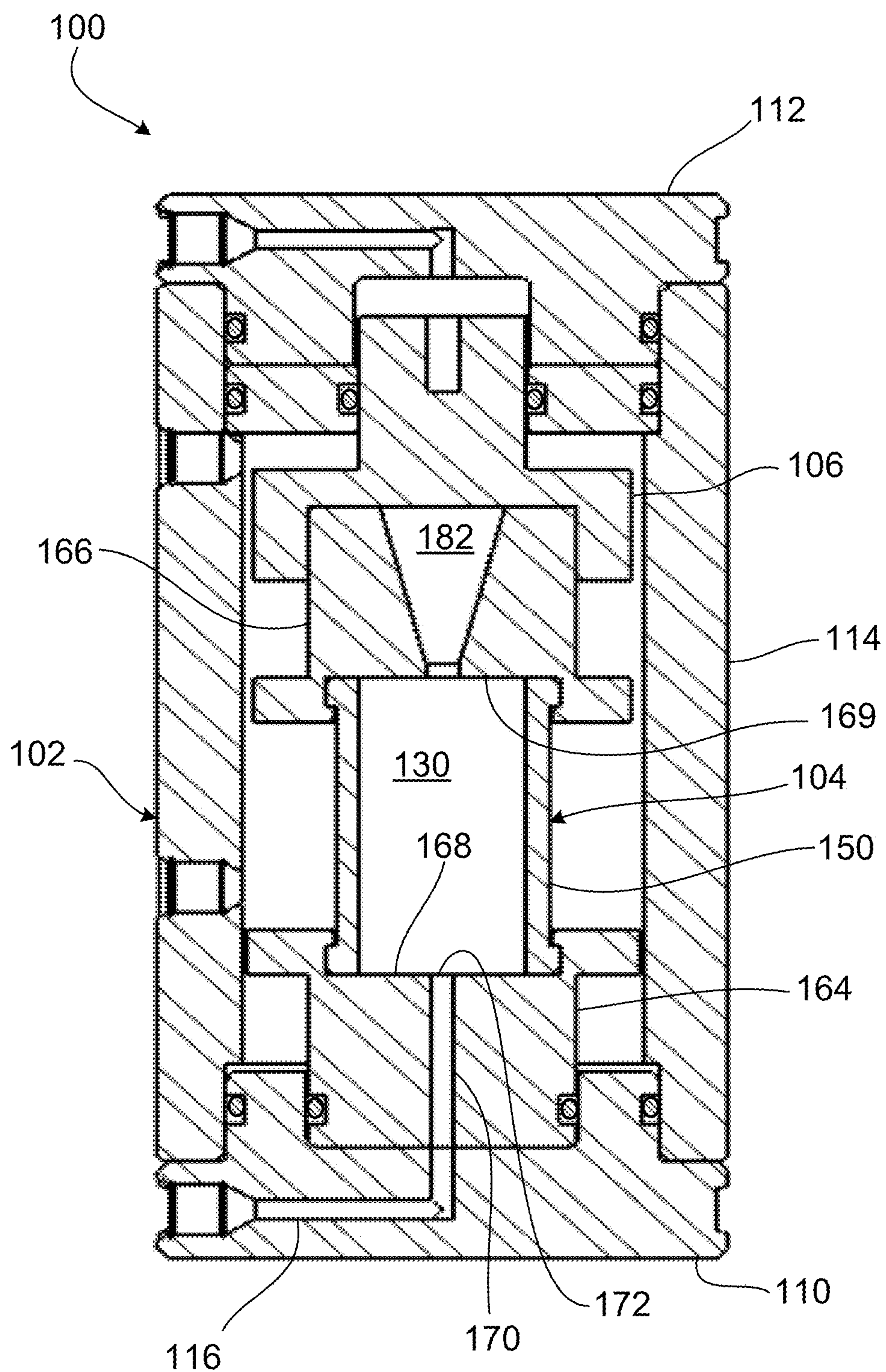


FIG. 2

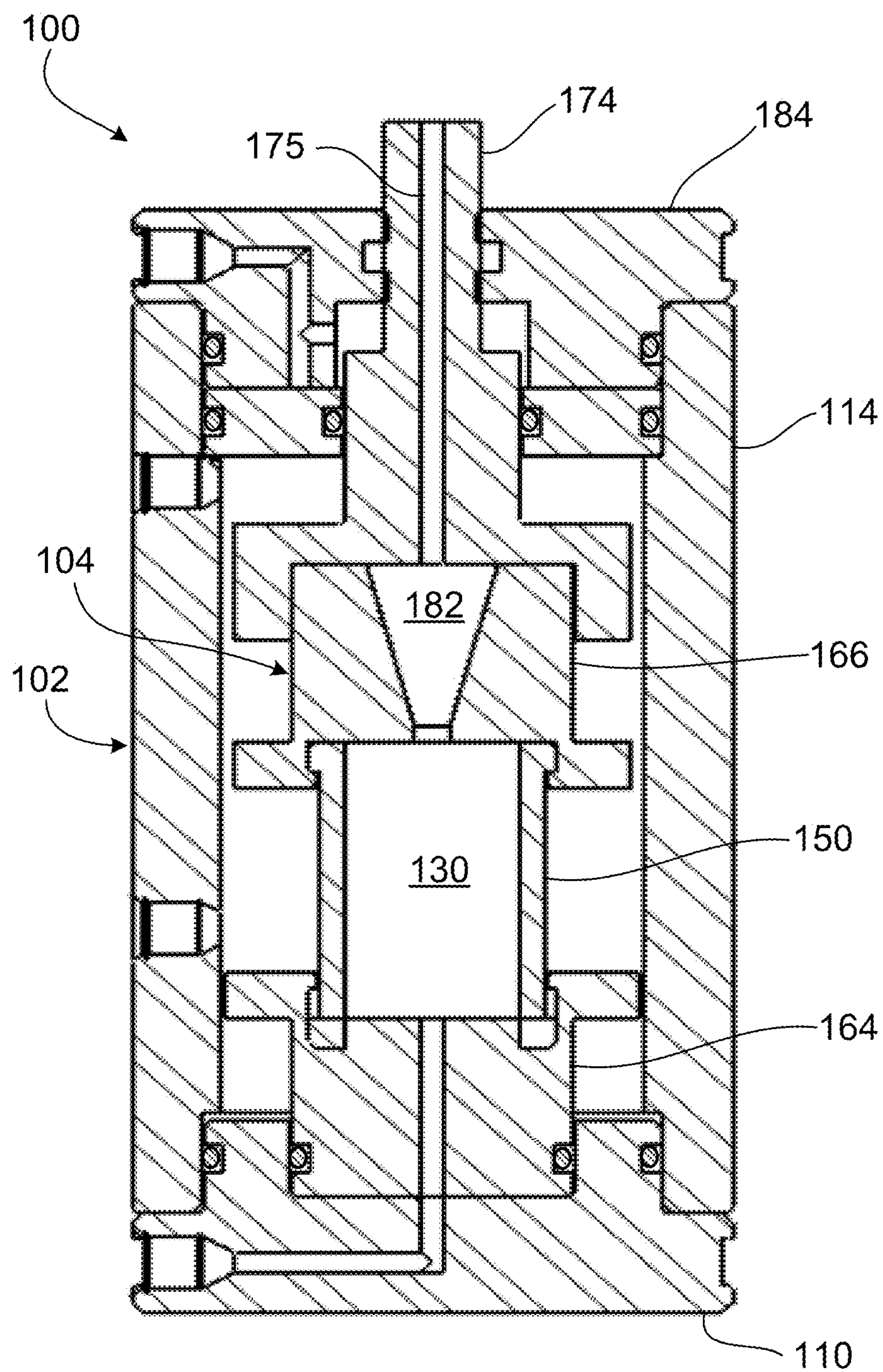


FIG. 3

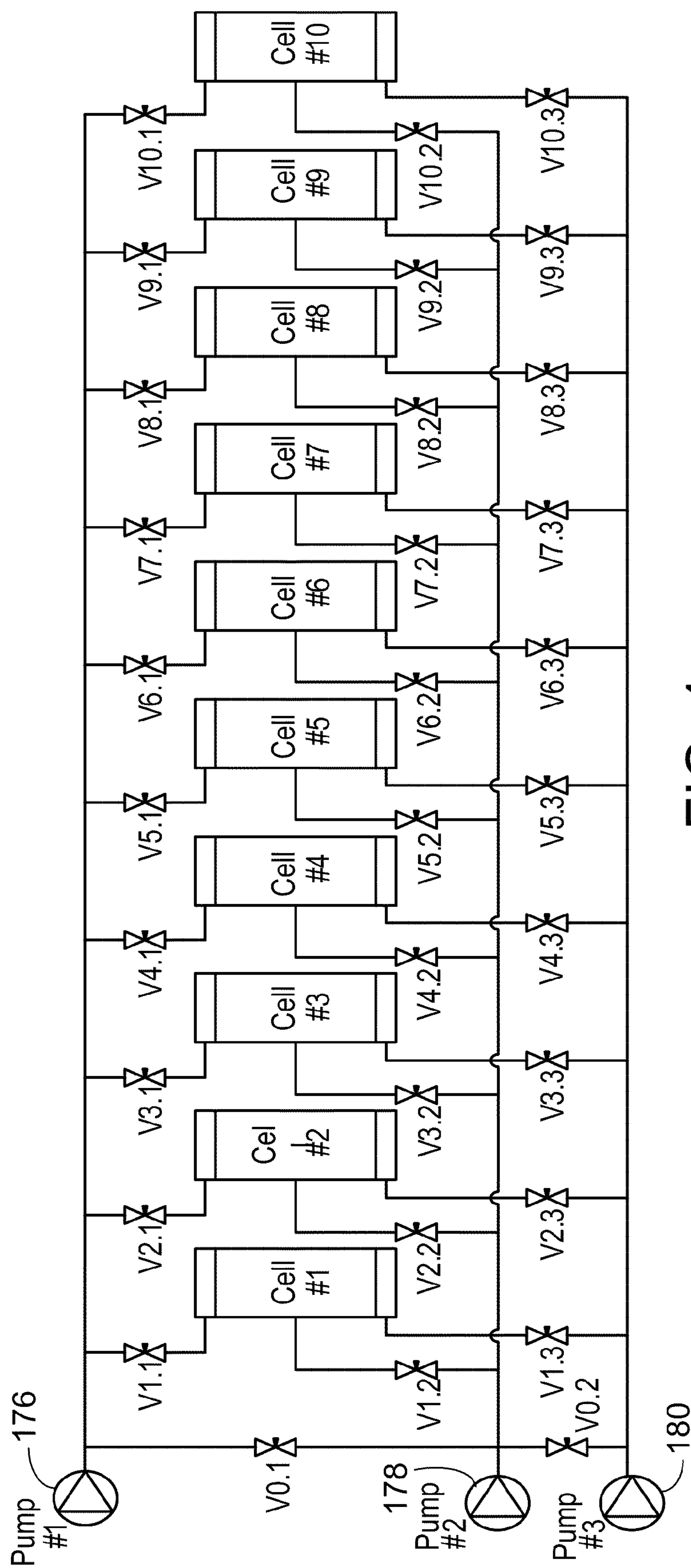


FIG. 4



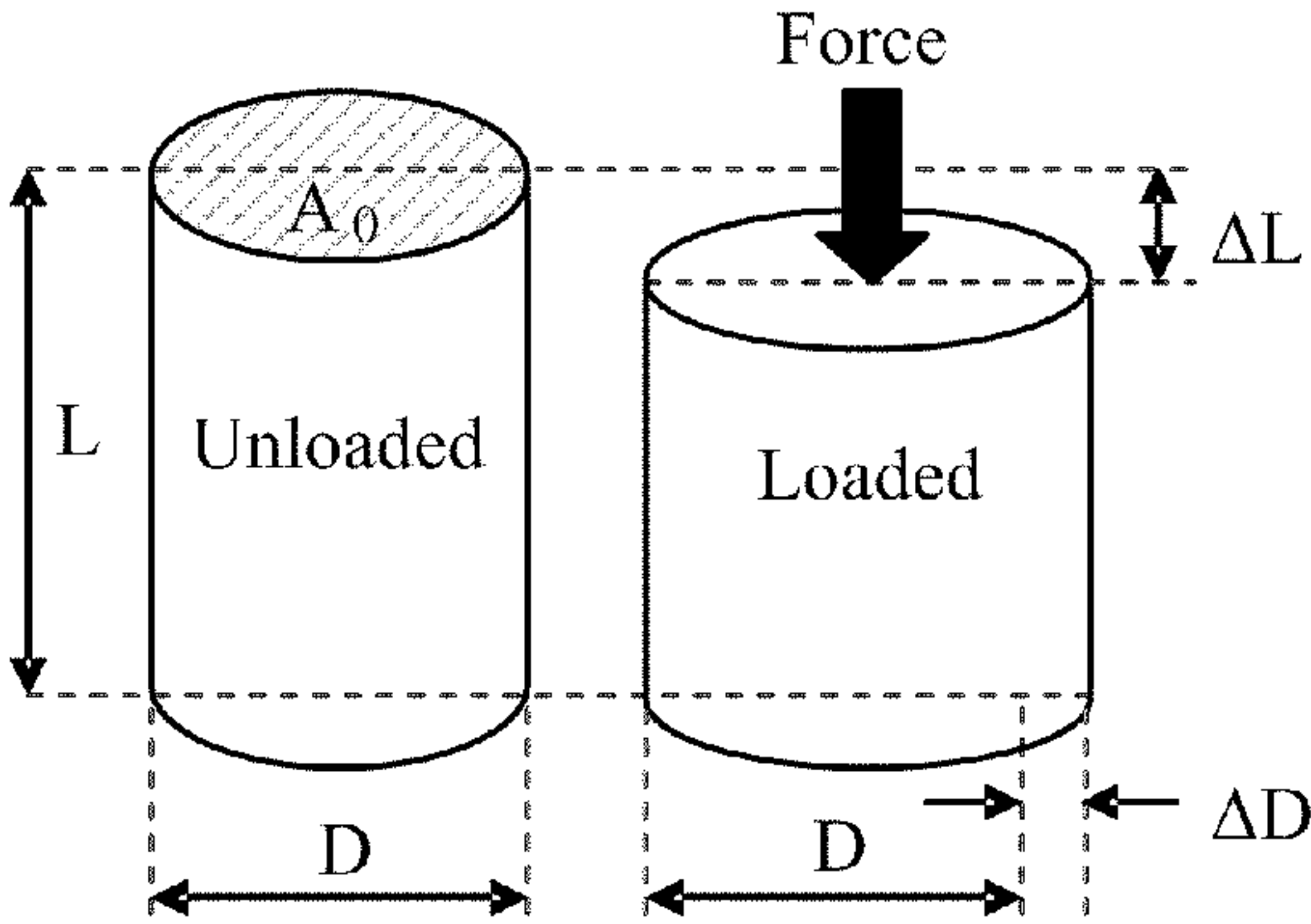


FIG. 5

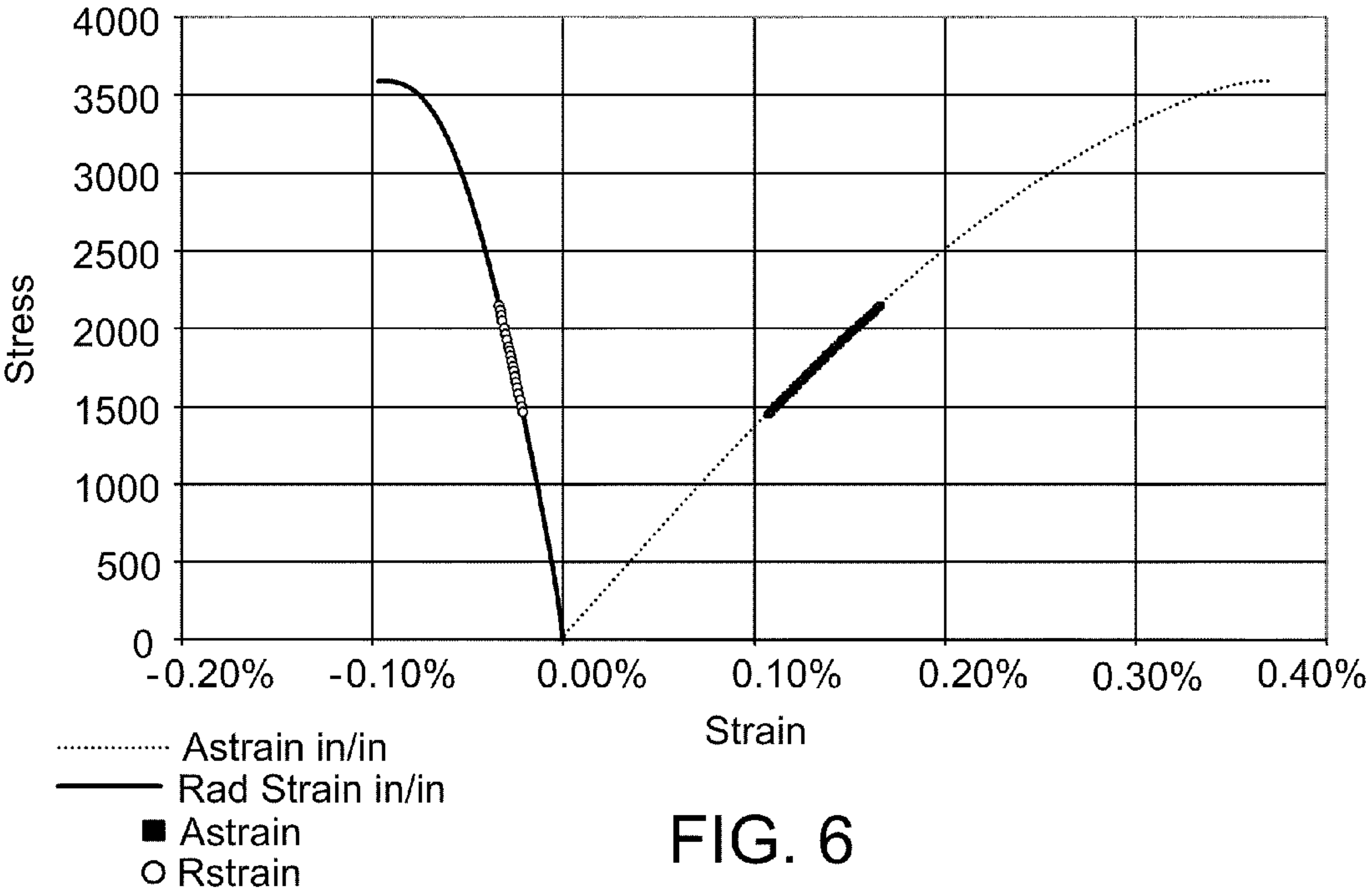


FIG. 6



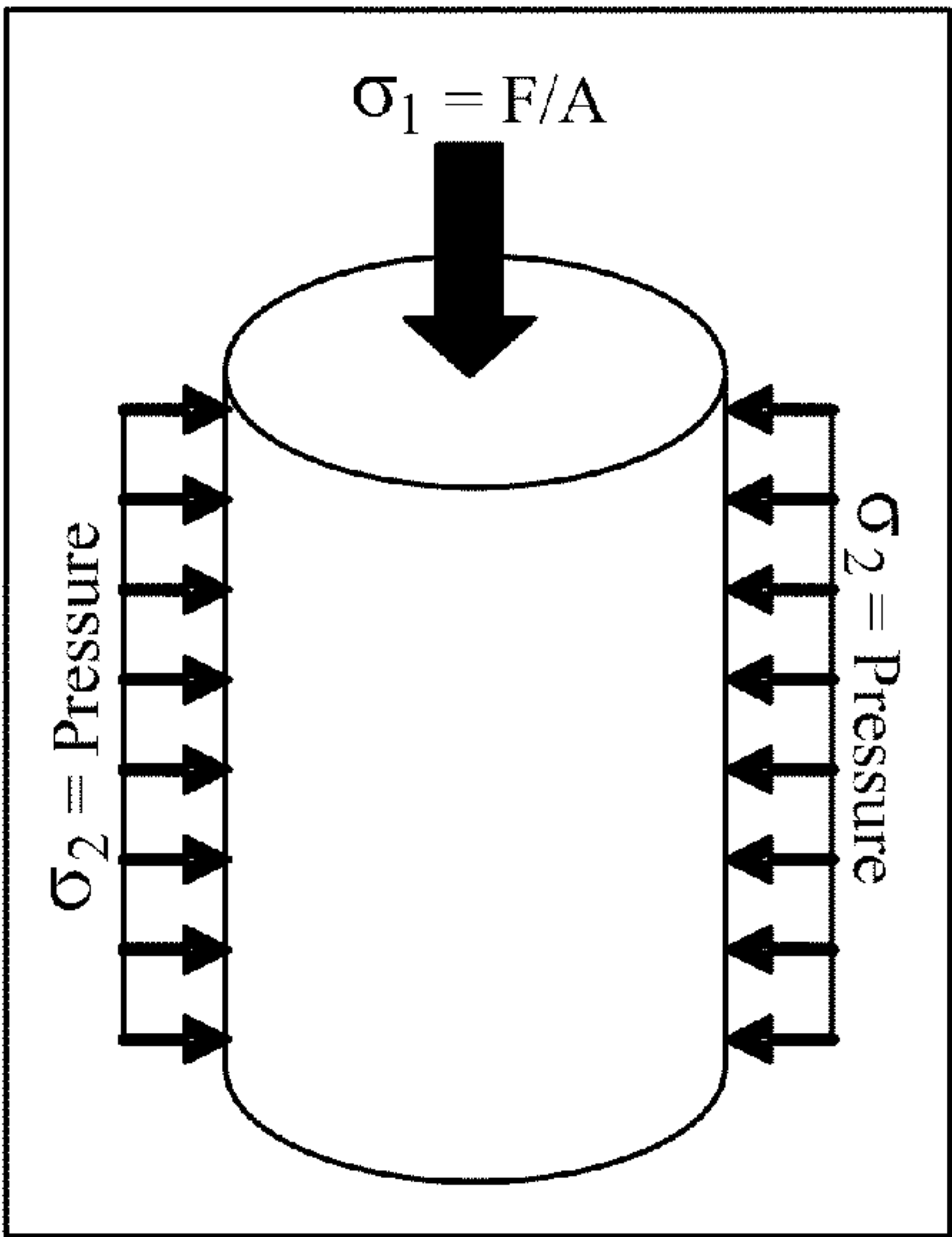


FIG. 7

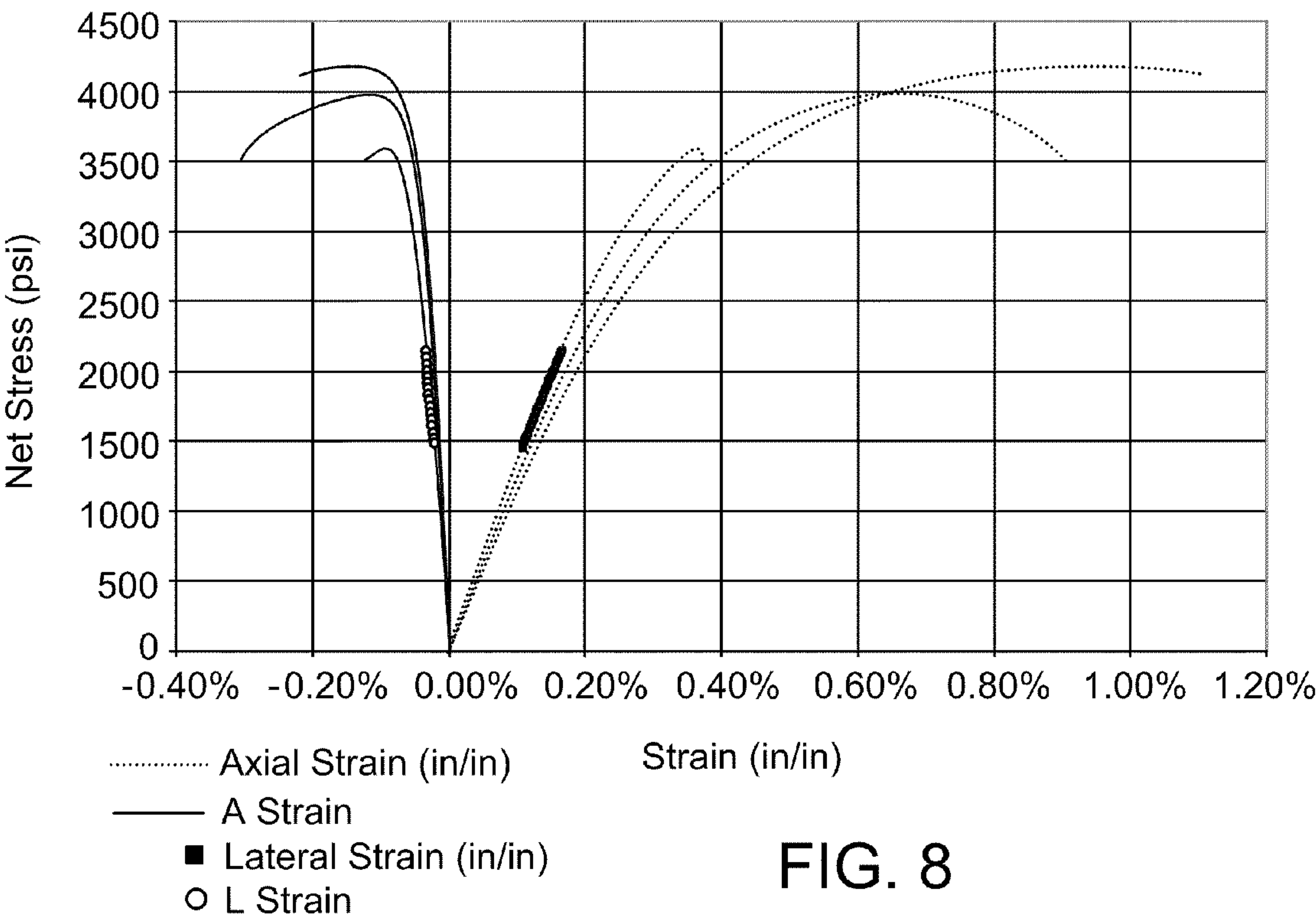


FIG. 8

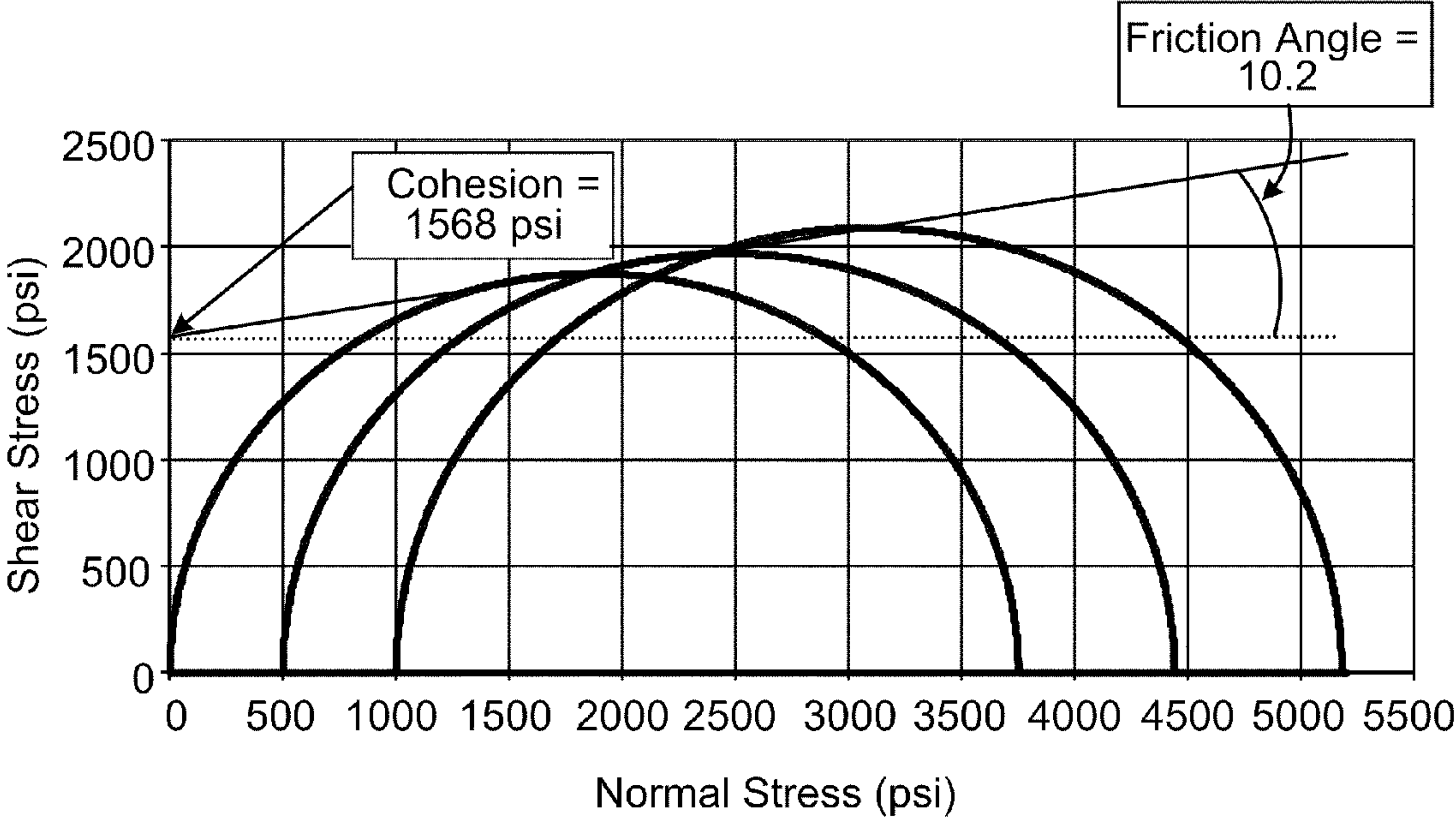


FIG. 9



## 1

## CEMENT TESTING

## TECHNICAL FIELD

This disclosure relates to measuring mechanical proper-  
ties.

## BACKGROUND

Some well bores, for example some oil and gas wells, are lined with a casing. The cemented casing stabilizes the sides of the well bore, prevents fluids (liquids or gases) in the well bore from entering the surrounding earth formations, and/or prevents fluids from zones other than the producing zones from entering the well bore.

In a typical cementing operation, cement is introduced down the well bore and into an annular space between the casing and the surrounding earth. The cement secures the casing in the well bore, and prevents fluids from flowing vertically in the annulus between the casing and the surrounding earth.

Different cement formulations are designed for a variety of well bore conditions, which may be above ambient temperature and pressure. In designing a cement formulation, a number of potential mixtures may be evaluated to determine their mechanical properties under various conditions.

Mechanical properties of subterranean formations in which well bores are to be formed can also affect the design of the well bores. In some instances, samples of subterranean formations are taken and subsequently evaluated to determine the mechanical properties of the formations.

## SUMMARY

Using the devices and methods described, cement samples can be cured at downhole conditions and the curing or cured sample subjected to tests including direct pull tensile strength tests without removal from the pressure vessel being used to maintain downhole conditions. This enables the application of drained or undrained unconfined compressive testing conditions, drained or undrained confined compressive testing conditions, drained or undrained unconfined tensile testing conditions, and drained or undrained confined tensile testing conditions as well as hydrostatic test conditions and derivatives.

In addition, cement samples can be tested while controlling both the pore pressure within the cement sample and the confining pressure applied to lateral exterior surfaces of a cement sample. This can allow, for example, the pore pressure to be controlled separately from the confining pressure. Accordingly, the pore pressure can be maintained at the curing pressure, set equal to the confining pressure, or set at another arbitrary value. This allows the user replicate tests with different pore and confining pressures to verify that the tensile strength/compressive strength of the sample is not affected by the relationship between pore and confining pressures.

In one aspect, systems for testing cement include at least one cement testing apparatus. The cement testing apparatus includes: a pressure vessel defining: a working volume inside the pressure vessel, the pressure vessel defining a first channel providing liquid communication through the pressure vessel to the working volume of the pressure vessel and a second channel providing liquid communication through the pressure vessel to the working volume of the pressure vessel; and a substantially tubular sample container defining a sample volume inside the sample container, the sample container

## 2

comprising walls extending from a first end with an opening to a second end with an opening, the sample container disposed in the working volume of the pressure vessel with the sample container substantially sealed to prevent liquid communication between the sample volume of the sample container and portions of the working volume of the pressure vessel outside the sample container. The sample container is positioned such that the first channel provides liquid communication through the pressure vessel to the sample volume of the sample container; and the second channel provides liquid communication through the pressure vessel to the portions of the working volume of the pressure vessel outside the sample container.

In one aspect, devices for testing cement include: a pressure vessel with a sample container inside an interior working volume of the pressure vessel, the pressure vessel configured to supply a first pressurized fluid to control a pore pressure of a cement sample and to supply a second pressurized fluid to lateral exterior surfaces of the sample container to provide a confining pressure that can be different than the pore pressure.

Embodiments can include one or more of the following features.

In some embodiments, the sample container includes: a first end member; a second end member; and a tubular member having walls that substantially sealed to the first end member and the second end member, the tubular member substantially more flexible than the first and second end members.

In some embodiments, the end members are configured to grip ends of a cement sample in the sample container. In some cases, each of the end members of the sample container defines an internal cavity that has a transverse first cross-sectional dimension adjacent the tubular member and a second transverse cross-section spaced apart from tubular member that is larger than the first cross-sectional dimension.

In some embodiments, the first end member of the sample container has a face extending across a first open end of the tubular member, the first end member defining a channel in liquid communication with the channel defined in the first end cap of the pressure vessel and extending to an opening in the face of the first end member. In some cases, the second end member has a face extending across a second open end of the tubular member, the second end member defining a frusto-conical cavity extending from an opening in the face of the second end member.

In some embodiments, the pressure vessel includes: a first end cap; a second end cap; and a sidewall member extending between the first end cap and the second end cap. In some cases, the first end cap of the pressure vessel defines the first channel through the end cap to the interior volume of the pressure vessel. The second end cap can define a third channel extending through the second end cap. In some cases, the piston extends through an aperture in the second end cap of the pressure vessel. The piston can define a channel extending through the piston, the channel in the piston providing liquid communication between an exterior of the pressure vessel and the second end member of the sample container.

In some embodiments, the at least one cement testing apparatus comprising a plurality of the cement testing apparatuses. In some cases, systems also include: a first pressure source operable to selectively supply pressurized liquid to the first channels of the plurality of cement testing apparatuses; and a second pressure source operable to selectively supply pressurized liquid to the second channels of the plurality of cement testing apparatuses.



## 3

In some embodiments, devices also include a piston which can apply tension or compression along an axis of the cement sample.

In one aspect, methods of testing cement include: controlling pore pressure in a cement sample inside a sample container disposed in a pressure vessel of a testing apparatus while the cement sample is curing to provide a first pressure in the cement sample; and simultaneously controlling a confining pressure applied to lateral exterior surfaces of the sample container to provide a second pressure that can be different than the first pressure. Embodiments can include one or more of the following features.

In some embodiments, methods also include: mixing a slurry of the cement sample at pressure conditions that are different than ambient pressure conditions; and transferring the slurry of the cement sample to the sample container for curing without exposure to ambient pressure conditions.

In some embodiments, methods also include: selecting end caps of the sample container based on tests to be performed; assembling the sample container by attaching the end caps to opposite ends of a substantially tubular sleeve which is more flexible than the end caps; and filling the sample container with slurry.

In some embodiments, methods also include: simultaneously setting initial pressure and/or temperature conditions in multiple testing apparatuses; isolating at least one of the testing apparatuses from others of the multiple testing apparatuses; and testing a mechanical property of cement sample(s) in the at least one of the testing apparatuses isolated from others of the multiple testing apparatuses. In some cases, methods also include: calculating a failure mode for the cement being tested based on testing a mechanical property of the cement sample in each of the multiple testing apparatuses.

In some embodiments, methods also include: curing a cement sample at first pressure conditions that are different than ambient conditions; and pulling on ends of the sample to apply axial tension to the sample while maintaining the sample at the first pressure conditions.

The methods and systems described can provide one or more of the following advantages.

The methods and systems described can allow a liquid slurry to cure at pressure and temperature conditions and, while curing or after cured, to be tested for volume changes, the mechanical response of the sample, and failure limits without removing curing, or cured, cement from the testing apparatus. Testing in the curing vessel can reduce the possibility that removal of the sample from the testing apparatus could impart damage to the sample that would influence subsequent results. Testing in the curing vessel can also save time and money, and reduces the limits on the ability to test curing in a small time window relative to cure associated with systems which require removal of the curing vessel for testing.

The methods and systems described can allow for independent control over pore pressure, confining pressure, and load magnitude, direction, and rate. In combination, the independent control of these parameters allows for multiple samples to be tested in replicate and with changes to one parameter at a time to provide statistics as well as different testing conditions.

The methods and systems described can provide the ability to cure and test cement at conditions that represent a cemented well casing.

The details of one or more embodiments are set forth in the accompanying drawings and the description below.

## DESCRIPTION OF DRAWINGS

FIG. 1 is a cross-section of a cement testing apparatus.  
FIG. 2 is a cross-section of a cement testing apparatus.

## 4

FIG. 3 is a cross-section of a cement testing apparatus.

FIG. 4 is a schematic of a cement testing system with multiple cement testing apparatuses.

FIG. 5 is a schematic of compressive testing of a cement sample.

FIG. 6 is a chart representing results of compressive testing of a cement sample.

FIG. 7 is a schematic of confined compressive testing of a cement sample.

FIGS. 8 and 9 are charts representing results of compressive testing with various confining loads.

Like reference symbols in the various drawings indicate like elements.

## DETAILED DESCRIPTION

The devices and methods described herein can allow an accurate measurement of mechanical properties and behaviors of cement formulations including, for example, tensile strength, compressive strength, shrinkage, and other properties. For example, a sample cement composition can be cured or partially cured at downhole conditions (e.g., temperatures and/or pressures elevated above ambient conditions) while monitoring chemical and bulk shrinkage and, at a specified time, changing the stress conditions applied to the sample while monitoring the mechanical response until failure occurs. Mechanical properties of the cement sample can be calculated based on the response of the sample to the differential stress conditions while the failure limits established by the material response or maximum stress endured before failure.

As used herein, “cement” and “cement composition” encompass a fluid mixture that hardens into solid, and may be any agent suitable to bond casing or other tubulars to well bore walls or to other tubing used for downhole applications. Some examples of cement include hydraulic cement (e.g., Portland cement formulations) and non-hydraulic cement (e.g., polymer resin formulations). As used herein, “curing” refers to the reactions through which cement hardens from a fluid mixture into a solid. In some instances, the devices and methods discussed herein can be used to measure mechanical properties at temperatures and pressures that simulate downhole conditions.

As used herein, “tube” and “tubular” encompass hollow members (e.g., hollow members made of metal, glass, rubber, or other material) with open ends. Such hollow members can be, but are not necessarily, cylindrical in shape.

As used herein, “piston” encompasses driving mechanisms including, for example, hydraulic pistons, power screws, linear actuators. Thus, the piston does not necessarily seal against the pressure vessels described below.

Referring to FIG. 1, a cement testing apparatus 100 that includes a pressure vessel 102, a sample container 104, and a piston 106 can be configured for testing the tensile strength of a cement sample. The illustrated testing apparatus 100 is substantially cylindrical in shape. However, in some embodiments, the testing apparatus 100 can have other shapes (e.g., can be substantially rectangular in shape). The modular nature of the pressure vessel 102 and the sample container 104 can facilitate providing different testing apparatus configurations. For example, the configuration illustrated in FIG. 1 can be used to test the tensile strength of a cement sample. As discussed in more detail below, the cement testing apparatus 100 can be configured for testing compression strength of the cement sample by choosing different components and configurations.



## 5

The pressure vessel **102** can have an interior working volume **108** defined by a first end cap **110**, a second end cap **112**, and sidewall member **114** formed by a hollow cylinder extending between the end caps **110**, **112**. The pressure vessel **102** can also include an isolation ring **115**.

The first end cap **110** defines a channel **116** extending through the first end cap **110**. The end cap **110** includes a shoulder **118** configured for press-fit engagement with sidewall member **114**. A seal **120** (e.g., an O-ring) is disposed in groove **122** and can limit (e.g., substantially prevent) leakage between the first end cap **110** and the sidewall member **114**. In some cases, a seal **120** such as an O-ring is disposed of in a groove **122** formed in the sidewall member **114** rather than in the first end cap **110**. In some cases, pressure vessels can use other sealing mechanisms including, for example, matching threads or metal-to-metal seals.

A bore **124** formed in the inner side of the first end cap **110** is sized to receive the lower end of the sample container **104**. The channel **116** in the first end cap **110** extends from a port **126** formed in a surface of the first end cap **110** to an opening **128** which provides liquid communication with an internal working volume **108** of the pressure vessel **102**. The opening **128** is positioned to provide liquid communication with an interior sample volume **130** of the sample container **104** when the sample container **104** is installed in the pressure vessel **102**. In the illustrated embodiment, the opening **128** is positioned in the center of the bore **124**. Some embodiments include more than one opening **128** and/or grooves along the face of bore **124** to distribute the fluid being used to control the pore pressure of the sample.

The port **126** can be configured to receive the end fitting (not shown) of tubing to convey fluid from a pressure source to the channel **116**. In some situations, a plug (not shown) can be used to substantially seal the port **126**. A slight groove **132** can be formed extending around part or all of the lateral outer surface of the first end cap **110**. The groove **132** can facilitate handling and sealing the pressure vessel **102**.

Terms of relative orientation such as upper, lower, above, and below are used relative to the orientation of embodiments shown in the figures being discussed. Although such terms do not require that the illustrated devices be oriented as shown in the figures, the cement testing apparatus **100** will typically be oriented as shown in FIG. 1 during use.

In the illustrated embodiment, the second end cap **112** is substantially similar to the first end cap **110**. The second end cap **112** includes a channel **116** extending from port **126** to opening **128**. The primary difference between the first end cap **110** and the second end cap **112** is that the bore **124** formed in the second end cap **112** is sized to receive a portion of the piston **106** where the bore **124** in the first end cap **110** is sized to receive the lower end of the sample container **104**.

The sidewall member **114** is attached to the end caps **110**, **112** by pressfit engagement between the sidewall member **114** and the end caps **110**, **112**. This configuration provides for easy assembly and disassembly of the pressure vessel **102**. However, this configuration can require an external locking mechanism (not shown) to hold the pressure vessel **102** together as a pressurizing fluid is supplied to the interior volume **108** of the pressure vessel. In some embodiments, the end caps **110**, **112** and the sidewall member **114** have matching threads on the exterior surfaces of the end caps **110**, **112** and the corresponding to interior surfaces of the sidewall member **114**. In these embodiments, the end caps **110**, **112** and the sidewall member **114** can be screwed together. Alternatively, the end caps **110**, **112** and the sidewall member **114** can also be attached using J-lock attachment mechanisms.

## 6

The sidewall member **114** can define two ports **126** with the upper port **126** positioned at or near the upper end of the interior volume **108** of the pressure vessel **102**. The ports **126** defined by the sidewall member **114** act as channels providing liquid communication through the pressure vessel **102** to the working volume of the pressure vessel. The ports **126** defined by the sidewall member **114** are positioned such that the ports **126** in the sidewall member **114** provide liquid communication through the pressure vessel **102** to the portions of the working volume **108** of the pressure vessel **102** outside the sample container **104** when the sample container **104** is installed in the pressure vessel **102**. The upper port **126** can be used to bleed off one fluid (e.g., air) while the interior volume **108** of the pressure vessel **102** is being filled with a denser second fluid (e.g., a petroleum based pressurizing fluid or water).

The isolation ring **115** has O-ring **120**/groove **122** combinations to limit fluid flow both between the isolation ring **115** and the sidewall member **114** and between the isolation ring **115** and the piston **106**. In some embodiments, rather than being a separate component, the isolation ring **115** is incorporated as part of the second end cap **112** of the pressure vessel **102**.

During use, the temperature of fluid in the pressure vessel **102** can range from room temperature to the high temperatures associated with downhole conditions (e.g., up to 1000 degrees Fahrenheit). The pressure of the fluid in the pressure vessel can range from atmospheric pressure to the high pressures associated with downhole conditions (e.g., up to 50,000 psi). The components of the pressure vessel **102** can be made from materials which are strong (e.g., able to maintain structural stability when subjected to high pressures), are durable (e.g., resistant to corrosion by the anticipated pressurizing fluids in the anticipated temperature and pressure ranges), and can be formed with the precision necessary to maintain substantially pressure-tight engagement between the components under testing conditions. For example, the end caps **110**, **112** and sidewall member **114** can be machined from stainless steel. Alternatively, the end caps **110**, **112** and sidewall member **114** can be formed using casting, laminating, or molding techniques from materials including, for example, steel, alloys, or composite fibers with a resin structure.

The sample container **104** includes walls **136** extending from a first end **138** with an opening **140** to a second end **142** with an opening **144**. The walls **136** defined the interior sample volume **130** of the sample container **104**. The sample container **104** has a substantially tubular shape. The sample container **104** can be disposed in the working volume **108** of the pressure vessel **102** with the sample container **104** substantially sealed to prevent liquid communication between the sample volume **130** of the sample container **104** and portions of the working volume **108** of the pressure vessel **102** outside the sample container **104**. For example, the walls **136** of the sample container **104** illustrated in FIG. 1 are formed by a first end member **146**, a second end member **148**, and a tubular member **150** having walls that can be substantially sealed to the first end member **146** and the second end member **148**. The tubular member **150** is more flexible than the first and second end members **146**, **148**. For example, in the embodiment illustrated in FIG. 1, the tubular member **150** can be formed of rubber and the first and second end members **146**, **148** can be formed of stainless steel. The first and second end members **146**, **148** have grooves **152** formed extending into inner surfaces of the end members **146**, **148**. The grooves **152** are sized and configured to receive flanges **154** extending outwards from the ends of the tubular member **150**. Engagement between the grooves **152** of the first and second end



members **146**, **148** and the flanges **154** of the tubular member **150** both provides a seal between and holds together the end members **146**, **148** and the tubular member **150**. Some embodiments use other methods of attachment including, for example, pressfit engagement, threaded engagement, or J-lock attachment mechanisms.

The lower end of the first end member **146** is received in the bore **124** of the first end cap **110**. The lower end of the first end member **146** receives a seal **120** (e.g., an O-ring) disposed in the groove **122** formed in an outer surface of the first end member **146**. In some cases, the seal **120** can be disposed of in a groove **122** formed in the inner surface of the sidewall member **114** rather than in the outer surface of the first end cap **110**.

The upper end of the first end member **146** includes outwardly extending flanges **156**. The outwardly extending flanges **156** of the first end member **146** do not, under normal conditions, contact the sidewall member **114**. The outwardly extending flanges **156** of the first end member **146** of the sample container **104** and the first end cap of the pressure vessel **102** include corresponding multiple threaded bores which allow the first end member **146** of the sample container **104** to be bolted to the first end cap of the pressure vessel **102**. These bores and bolts are not shown because they do not lie in the plane of the cross-section shown in FIG. 1. Some embodiments use other methods of attachment including, for example, pressfit engagement, threaded engagement, or J-lock attachment mechanisms.

The lower end of the second end member **148** also has outwardly extending flanges **156**. The outwardly extending flanges **156** of the second end member **148** include multiple threaded bores **158** which allow the piston **106** to be bolted to the second end member **148** of the sample container **104**. In the illustrated embodiment, no additional sealing mechanisms are provided to limit the flow of fluid between the piston **106** and the sample container **104**. However, some embodiments include sealing mechanisms between the piston **106** and the sample container **104** such as the O-ring **120**/groove **122** combination used elsewhere in the testing apparatus **100**.

The end members **146**, **148** are configured to grip ends of a cement sample in the sample container. For example, in the illustrated embodiment, the end members **146**, **148** of the sample container **104** define an internal cavity **160** that is part of the sample volume **130** of the sample container **104**. The internal cavities **160** of the end members **146**, **148** each have a transverse first cross-sectional dimension **d1** adjacent the tubular member **150** and a second transverse cross-section **d2** spaced apart from tubular member **150** that is larger than the first cross-sectional dimension **d1**.

The end members **146**, **148** can be machined from stainless steel. Alternatively, the end members **146**, **148** end caps **110**, **112** can be formed using casting, laminating, or molding techniques from materials including, for example, steel, alloys, or composite fibers with a resin structure. The tubular member **150** can be molded from rubber. Alternatively, the tubular member **150** can be formed using machining or laminating techniques from materials including, for example, epoxy or resins.

The piston **106** has a first end that receives the second end member **148** of the sample container **104** and a second end that is received by the isolation ring **115** and the bore **124** of the second end cap **112** of the pressure vessel **102**. Threaded bores **156** in flanges extending outward from the first end of the piston allow the piston **106** to be bolted to the second end member **148** of the sample container **104**. The second end of the piston **106** defines a threaded bore **162**. The threaded bore

**162** is provide to help in disassembling the apparatus. After testing, a threaded tool or bolt can be screwed into threaded bore **162** to provide a point of purchase for applying force to detach the piston **106** from the sample container **104**. The piston can be machined from stainless steel. Alternatively, the piston **106** can be formed using casting, laminating, or molding techniques from materials including, for example, steel, alloys, or composite fibers with a resin structure.

Testing apparatuses can include sensors to measure parameters used to calculate properties of samples being tested. For example, testing apparatus **100** may include linear variable displacement transducers (LVDTs) positioned at 120 degree intervals around a circle around the end members **146**, **148** of the sample container **104** or in other suitable positions. The average reading of the three LVDTs can be used to characterize the length change of the sample during testing. In addition, LVDTs can be used to measure tangential changes in deformation of the sample. Other sensors, such as extensometers, electrical strain gauges or fiber optic strain gauges, can be used in addition to or in place of the LVDTs to measure relevant parameters. For example, four strain gauges (two vertical and two tangential) could be attached to interior surfaces of tubular member **150** to provide material data that would be difficult to obtain otherwise. Alternatively, strain gauges could be attached to exterior surfaces of tubular member **150**. Similarly, the amount of fluid (e.g., water) pumped into the pressure vessel **102** as the cement cures can provide a measure of cement shrinkage. Pressure and temperature sensors can be included to measure pressures and temperatures present during testing. Pressure, temperature, and strain sensors can be used as feedback to control the test process. For example, pressure sensors can control the pump to pressure up or down dependent upon a controlled set point. Likewise, the piston loading the test specimen can be actuated in a direction depending on the deflection or strain measurements experienced by the sample.

Temperature can be controlled to simulate downhole conditions during testing or at other times. For example, in testing cement, the testing apparatus **100** and cement slurry can be preheated during mixing. The desired temperature can be maintained as the sample cement composition cures using external heating elements (e.g., heater coils or stainless steel heater bands) or placing the testing apparatus **100** in an oven. Likewise the testing apparatus could also be heated in a profile that simulates the temperature a cement system would experience from mixing, placement, and curing during cementing a wellbore casing string.

As shown in FIG. 2, the cement testing apparatus **100** can also be configured for compression testing of a cement sample. In this configuration, the pressure vessel **102** can include the same end caps **110**, **112** and sidewall member **114** described above with respect to FIG. 1. Sample container **104** can include the same tubular member **150** described above with respect to FIG. 1. The primary difference between configurations is that the sample container **104** includes different end members.

A first end member **164** of the sample container **104** has a face **168** extending across a first open end of the tubular member **150**. The first end member **164** defines a channel **170** in liquid communication with the channel **116** defined in the first end cap **112** of the pressure vessel **102** and extending to an opening **172** in the face **168** of the first end member **164**. The combined channels enable a pressure source (not shown) connected to the port and the first end cap **110** of the pressure vessel **102** to control the pore pressure of a cement sample in the sample volume **130** of the sample container **104**. A second end member **166** of the sample container **104** has a face **169**



extending across a second open end of the tubular member 150. The second end member 166 defines a buffer space which can be used to compensate for the expansion or contraction of a cement sample during hydration and/or curing. In the illustrated embodiment, the buffer space is a frusto-conical cavity extending from an opening in the face 169 of the second end member 166. In some cases, other shapes can be used.

As shown in FIG. 3, the cement testing apparatus 100 can also be configured such that a slurry of a cement sample can be mixed at pressure and temperature conditions that are different than ambient pressure conditions and then be transferred to the sample container for curing without exposure to ambient pressure conditions. In this configuration, the sample container 104 can include the same end members 164, 166 as described above with respect to FIG. 2. The primary difference between the configurations shown in FIG. 2 and in FIG. 3 is that a piston 174 has an end that extends through an aperture in a second end cap 184 of the pressure vessel 102. The piston 174 defines a channel 175 extending through the piston 174. The channel 175 in the piston 174 provides liquid communication between an exterior of the pressure vessel 102 and the second end member 166 of the sample container 104. In the illustrated embodiment, the channel 175 can discharge a cement slurry into the buffer space 182.

In the illustrated embodiment, the piston 174 is used in a cement testing apparatus 100 configured for testing the compressive strength of the cement sample. In some cases, a similar piston can be used in a cement testing apparatus 100 configured for testing the tensile strength of the cement sample. For example, the piston 174 and the end cap 184 of the pressure vessel 102 can be used in place of the piston 106 and the end cap 112 shown in FIG. 1.

The testing apparatus 100 can be used to perform a variety of tests on cement samples including, for example, tests for uniaxial compressive strength, triaxial compressive strength, uniaxial tensile strength, and hydrostatic strength. After determining which test a specific testing apparatus 100 will be used to perform, the appropriate components of the specific testing apparatus 100 are assembled and filled with a slurry of the cement to be tested.

In some embodiments, systems can include multiple testing apparatuses 100 attached in parallel to three pressure sources (e.g., pumps 176, 178, 180) as shown in FIG. 4. The pump 176 can be used to apply the desired load for a specific test, the pump 178 can be used to control the confining pressure applied to lateral side surfaces of the sample, and the pump 180 can be used to control the pore pressure of the sample. Running specific tests on multiple testing apparatuses can provide the data necessary to run statistical analyses on the resulting strength and property measurements. Running different tests on multiple testing apparatuses can provide data to build performance envelopes for the cement system under evaluation.

A user preparing and filling the testing apparatus 100 for tensile strength testing of a cement sample begins by selecting the appropriate sample container end member (e.g., end member 146) and inserting the end member 146 into pressfit engagement with the first end cap 110 of the pressure vessel 102. The end member 146 of the sample container 104 can then be bolted to the first end cap 110 of the pressure vessel 102. The tubular member 150 can then be inserted into engagement with the first end member 146 of the sample container 104. The second end member 148 of the sample container 104 can then be attached to the tubular member 150. Measurement devices as discussed above can then be attached to measure the diameter of the tubular member 150

and the distance between the end members 146, 148. The sidewall member 114 of the pressure vessel 102 can then be slid down over the components 146, 148, 150 of the sample container 104. The sidewall member 114 can then be attached to the first end cap 110 of the pressure vessel 102. At this time, the sample volume 130 of the sample container 104 can be filled with the cement slurry to be tested. The piston 106 can then be placed in position and bolted to the second end member 148 of the sample container 104. The lower port 126 in the sidewall member 114 can be used to fill the portion of the working volume 108 of the pressure vessel 102 outside of the sample container 104 with a temperature-stable pressurizing fluid (e.g., water). Air being displaced by the pressurizing fluid can be vented through the upper port 126 in the sidewall member 114. The isolation ring 115 and the second end cap 112 of the pressure vessel 102 can then be installed.

A user preparing and filling the testing apparatus 100 for tensile strength testing of a cement sample mixed at other than ambient conditions uses a generally similar process to the previously discussed tensile strength testing preparation. However, the piston 174 and associated end cap 184 are used rather than piston 106 and end cap 112. After the testing apparatus 100 is assembled, the sample volume 130 of the sample container 104 and the working volume 108 of the pressure vessel 102 can be filled with the pressurizing fluid. The heated and pressurized cement slurry can be pumped into the sample volume 130 through channel 175 in the piston 174. This approach allows mixing a slurry of the cement sample at pressure conditions that are different than ambient pressure conditions; and then transferring the slurry of the cement sample to the sample container for curing without exposure to ambient pressure conditions.

A user preparing and filling the testing apparatus for compressive strength testing of a cement sample mixed at ambient conditions uses a generally similar process to the previously discussed tensile strength testing preparation for a sample mixed at ambient conditions. However, end members 164, 166 rather than end members 146, 148 are used for the sample container 104. The sample volume 130 is filled through the buffer space 182. The cement slurry can be added to the sample container 104 to fill the tubular member 150 and part of the buffer space 182. The buffer space 182 can compensate for the expansion or shrinkage of the cement sample during curing and increase the likelihood that the interior of the tubular member 150 is full when testing begins.

A user preparing and filling the testing apparatus 100 for compressive strength testing of a cement sample mixed at other than ambient conditions uses generally similar process. The sample container 104 is assembled with the compressive strength testing end members 164, 166. The pressurizing slurry piston 174 is used with the associated end cap 184 of the pressure vessel 102.

Cements shrinkage and/or expansion can be monitored during curing by directly measuring the size of the sample and/or by volumetric measurements based on the amount of fluids provided to the working volume 108 of the pressure vessel 102 and the sample volume 130 of the sample container 104. The volume of fluid provided to the working volume 108 of the pressure vessel 102, or the changes in the measurements of sample size, can provide an indication of bulk shrinkage. The volume of fluid provided to the sample volume 130 of the sample container 104 can provide an indication of chemical shrinkage.

The testing apparatuses 100 can be used to perform both compressive and tensile strength tests. Compressive tests are performed by applying an axial compressive force to the sample as shown in FIG. 5. In contrast, direct tensile strength



## 11

tests are performed by applying an axial pulling force on the sample. In either compressive or tensile strength tests, the force is gradually increased until the cement sample has failed, or seen the maximum amount of force available has been applied. Measurements are made of the force, axial deformation ( $\Delta L$ ), and diametric deformation ( $\Delta D$ ). From this information the engineering parameters normal stress ( $\sigma$ ), axial strain ( $\epsilon_a$ ), lateral strain ( $\epsilon_l$ ), Young's Modulus (YM) and Poisson's Ratio (PR) as well as the compressive strength (CS) can be determined.

Normal stress is defined as a force applied perpendicular to a unit of area. Axial strain is defined as the amount of dimensional change ( $\Delta L$ ) relative to the original length ( $L_0$ ) in the direction of primary stress. Lateral strain is defined as the amount of dimensional change ( $\Delta D$ ) relative to the original Diameter ( $D_0$ ) in a direction perpendicular to the primary stress.

The results of cement compressive tests can be presented as stress versus strain as shown in FIG. 6. In rock mechanics, compressional stress is typically defined as positive; thus, a reduction in dimension is presented as a positive strain. For the example stress-strain curve, the positive strain ( $\epsilon$ ) portion of the x-axis is equivalent to the axial strain ( $\epsilon_a$ ). The curve associated with positive strain is measured and mathematically derived from the axial deformation and pressure sensors in an individual testing apparatus 100. When cement is deformed axially in compression, it has the tendency to expand in the lateral direction. This results in a strain value that is negative. The curve associated with the negative strain values, or lateral strain ( $\epsilon_l$ ) is derived from the diametric deformation and pressure sensors in an individual testing apparatus 100.

Young's Modulus (YM) is a measure of the stiffness of an isotropic elastic material and is defined as the ratio of the axial stress over the axial strain in the range of stress in which the material has a tendency to deform linearly under stress. In moderate stress levels, cement typically deforms linearly and therefore its modulus is often reported. The Young's Modulus of a cement sample is determined experimentally by taking the slope of a linear regression on the stress-strain plot over a known stress range (see, e.g., the darkened portion of the positive strain curve in FIG. 6). In other methods, the Young's Modulus can be derived on different portions of the stress-strain curve or from zero to a point along the stress-strain curve.

Poisson's Ratio, which characterizes the lateral deformation as a function of axial deformation is the ratio, when a sample object is stretched, of the contraction or transverse strain (perpendicular to the applied load), to the extension or axial strain (in the direction of the applied load). The Poisson's Ratio of a cement sample is determined experimentally by calculating the ratio of lateral strain change to axial strain change experienced over the same stress range.

The unconfined compressive strength is the maximum stress that cement can endure when the confining pressure (e.g., the pressure in the working volume 108 of the pressure vessel 102 outside of the sample container 104) is zero. It is determined experimentally by destructively testing the cement. The maximum stress recorded at failure is the unconfined compressive strength.

Compressive testing can also be performed with stresses applied in more than one direction. For example, a confining pressure can be used to apply fluid pressure on the lateral side surfaces of a sleeved test specimen as shown in FIG. 7. This results in a stress ( $\sigma_2$ ) along the curved surface equal to the fluid pressure. The primary stress ( $\sigma_1$ ) can still be applied mechanically through the hydraulic system. The unconfined

## 12

compression test is a simplified version of the triaxial test with the confining pressure ( $\sigma_2$ ) left equal to zero. The engineering parameters, previously discussed, can also be determined for a test result where the stress-strain relationship is recorded.

Initially, in confined compressive strength testing the fluid pressure ( $\sigma_2$ ) and the mechanical load ( $\sigma_1$ ) are simultaneously brought to a predetermined value for the confining pressure. Then the mechanical load ( $\sigma_1$ ) is increased (or decreased depending on load direction) until sample failure occurs (while the confining pressure ( $\sigma_2$ ) is held constant). The maximum load the sample withstands minus the confining stress ( $\sigma_2$ ) is defined as the confined compressive strength. The material response and failure limits are influenced by various confining loads. For example, FIG. 8 illustrates exemplary compressive test results at three confining pressures: 0 (or unconfined), 500, and 1,000 psi. The slope of the linear portion of the stress-strain curves change marginally while the ultimate stress experienced is greatly different. As confining pressure increases, the compressive strength increases.

Stress at a point in a solid body has both shear and normal stress components. Analysis of the stress-state in the simple test specimen exposed to normal stresses of  $\sigma_1$  and  $\sigma_2$  at the boundary actually results in both shear and normal stresses at points within the sample. The transformation equation relating the shear and normal stresses takes the form of "Mohr's circle." This concept is important for cement testing because physical observations of failed samples subjected to normal stresses are found to actually fail in shear. This is especially true when cement is tested in a confined state. As shown on FIG. 9, Mohr's circle for a confined compressive test can be plotted as a half-circle on stress-strain plot in which the confining pressure ( $\sigma_2$ ) for the test is the beginning of each half circle and the maximum stress at failure ( $\sigma_1$ ) for the test is the end of each half circle. Each circle has a radius equal to  $(\sigma_1 - \sigma_2)/2$  which is also the maximum shear stress experienced during the test or failure limit of the test.

A failure envelope can be defined by performing several confined tests each yielding a Mohr-circle. The failure limit for each case is used to establish a failure envelope which is defined by the Mohr-Coulomb shear failure line or similar model. This line's y-intercept is the "Cohesion" of the sample and the slope is the "Friction Angle" of the sample. A linear regression of the maximum axial stress ( $\sigma_1$ ) versus the confining stress ( $\sigma_2$ ) is used to determine the friction angle and cohesive strength. The slope,  $\alpha$ , of the linear least squares fit is used to calculate friction angle ( $\Phi$ ) while the cohesive strength ( $S_0$ ) is determined using Unconfined Compressive Strength and the friction angle. Subsequently, a stress state represented by a Mohr-Circle can be compared to the Mohr-Coulomb shear failure envelope. If the circle crosses the envelope, then a shear failure is expected.

The maximum "pulling" stress that a cement sample can withstand is defined at the tensile strength (TS). The tensile strength of a sample can be tested indirectly or directly. Direct testing (e.g., by actually pulling on the sample until it breaks) can provide different, possibly more accurate results than indirect testing. However, direct testing typically requires removing the sample from the pressure vessel in which it has been cured.

The results of tensile strength testing can be plotted on stress-strain curves and analyzed in similar fashion to that discussed above for analyzing the results of compressive testing.

Multiple testing apparatuses 100 can be attached to the pressure sources 176, 178, 180 as shown in FIG. 4. The valves



can all be opened and in the pressure sources 176, 178, 180 used to bring the system to an initial pressure for curing. As discussed above, the temperature of the system can also be controlled. Depending on the specific test being conducted, an individual testing apparatus 100 may be brought to curing pressure before receiving the cement sample or may be brought to curing pressure after receiving the cement sample to be tested. After initial temperature and pressure conditions are set, the cement samples can be cured for a desired period of time (e.g., 8-72 hours, up to 14 days, or up to 6 months). Testing can be preformed on semisolid (e.g., partially cured) or solid (e.g., cured) samples.

After the cement samples have been cured for the desired period of time, the tests can be performed. The valves V0.1 and V0.2 can be closed to isolate the pumps 176, 178, 180 from each other. All valves, except the valves associated with the particular testing apparatus 100 being used to perform the current test, can be closed to lock in pressure in the other testing apparatuses 100. The pumps 176, 178, 180 can then be operated to perform the test that the particular testing apparatus 100 is configured for by controlling the pumps as indicated in (but not limited to) Table 1. In particular, the load pressure can be increased or decreased as indicated in Table 1 until the cement sample fails. Failure of the cement sample can be indicated, for example, by a sudden change in sample dimensions.

The system can include a control system operable to automatically control pumps 176, 178, 180, valves, and heating mechanisms to carry out specified tests. In some cases, pumps 176, 178, 180, valves, and heating mechanisms can be manually operated. Data from the instrumentation can be recorded using a data acquisition system and used for control of the system.

TABLE 1

Name	Insitu Uniaxial Compressive Strength	Insitu Triaxial Compressive Strength #1	Insitu Triaxial Compressive Strength #2	Insitu Uniaxial Tensile Strength	Insitu Hydrostatic Strength
Confinement Pressure (Pump #2)	= $\sigma_0$ *	> $\sigma_0$	$\neq \sigma_0$	= $\sigma_0$	=Pump #1
Load Pressure Direction (Pump #1)	Increasing from $\sigma_0$	Increasing from $\sigma_0$	Increasing from $\sigma_0$	Decreasing from $\sigma_0$	Increasing from $\sigma_0$
Pore Pressure (Pump #3)	= $\sigma_0$	= $\sigma_0$	= $\sigma_0$	= $\sigma_0$	= $\sigma_0$

\*where  $\sigma_0$  is the initial pressure used during curing.

The configuration of testing apparatuses 100 allow the pore pressure to be controlled separately from the confining pressure. Accordingly, the pore pressure can be maintained at the curing pressure, set equal to the confining pressure, or set at another arbitrary value. This allows the user replicate tests with different pore and confining pressures to verify that the tensile strength/compressive strength of the sample is not affected by the relationship between pore and confining pressures.

The methods and systems described can allow a liquid slurry to cure at pressure and temperature conditions and, while curing or after cured, to be tested for volume changes, the mechanical response of the sample, and failure limits without removing curing, or cured, cement from the testing apparatus. Testing in the curing vessel can reduce the possibility that removal of the sample from the testing apparatus could impart damage to the sample that would influence

subsequent results. Testing in the curing vessel can also save time and money, and reduces the limits on the ability to test curing in a small time window relative to cure associated with systems which require removal of the curing vessel for testing.

The methods and systems described can allow for independent control over pore pressure, confining pressure, and load magnitude, direction, and rate. In combination, the independent control of these parameters allows for multiple samples to be tested in replicate and with changes to one parameter at a time to provide statistics as well as different testing conditions.

The methods and systems described can provide the ability to cure and test cement at conditions that represent a cemented well casing.

A number of embodiments have been described. Nevertheless, it will be understood that various modifications may be made. For example, in some embodiments, the upper end member of the sample container is provided by the piston and the lower end member of the sample container is provided by the lower end cap of the pressure vessel. Accordingly, other embodiments are within the scope of the following claims.

What is claimed is:

1. A system for testing cement, the system comprising:  
at least one cement testing apparatus, each cement testing apparatus comprising:  
a pressure vessel defining:  
a working volume inside the pressure vessel, the pressure vessel defining a first channel providing liquid communication through the pressure vessel to the working volume of the pressure vessel and a second channel providing liquid communication through the pressure vessel to the working volume of the pressure vessel; and

a substantially tubular sample container comprising walls extending from a first end with a first end member having an opening to a second end with a second end member having an opening, the end members configured to grip ends of a cement sample in the sample container, the sample container disposed in the working volume of the pressure vessel with the sample container substantially sealed to prevent liquid communication between a sample volume, defined by the first and second end members and a tubular member of the sample container, and portions of the working volume of the pressure vessel outside the sample container, the tubular member comprising a specified material that is more flexible than a material of the first and second end members, the tubular member comprising walls that are substantially sealed to the first end member and the second end member;



## 15

wherein the sample container is positioned such that the first channel provides liquid communication through the pressure vessel to the sample volume of the sample container; and the second channel provides liquid communication through the pressure vessel to the portions of the working volume of the pressure vessel outside the sample container.

2. The system of claim 1, each of the end members of the sample container defining an internal cavity that has a first transverse cross-sectional dimension adjacent the tubular member and a second transverse cross-section spaced apart from tubular member that is larger than the first cross-sectional dimension.

3. The system of claim 1, the first end member of the sample container having a face extending across a first open end of the sample container, the first end member defining a channel in liquid communication with a channel defined in a first end cap of the pressure vessel and extending to an opening in the face of the first end member.

4. The system of claim 3, the second end member having a face extending across a second open end of the sample container, the second end member defining a frusto-conical cavity extending from an opening in the face of the second end member.

5. The system of claim 1, the pressure vessel comprising:  
a first end cap;  
a second end cap; and  
a sidewall member extending between the first end cap and the second end cap.

6. The system of claim 5, the first end cap of the pressure vessel defining the first channel through the end cap to the working volume of the pressure vessel.

7. The system of claim 6, the second end cap defining a third channel extending through the second end cap.

8. The system of claim 5, further comprising a piston extending through an aperture in the second end cap of the pressure vessel.

9. The system of claim 8, the piston defining a channel extending through the piston, the channel in the piston providing liquid communication between an exterior of the pressure vessel and the second end member of the sample container.

10. The system of claim 1, the at least one cement testing apparatus comprising a plurality of the cement testing apparatuses.

## 16

11. The system of claim 10, the system further comprising:  
a first pressure source operable to selectively supply pressurized liquid to the first channels of the plurality of cement testing apparatuses; and

a second pressure source operable to selectively supply pressurized liquid to the second channels of the plurality of cement testing apparatuses.

12. The system of claim 1, the material of the tubular member comprising a rubber material, and the material of the first and second end members comprising a steel material.

13. A system for testing cement, the system comprising:  
at least one cement testing apparatus, each cement testing apparatus comprising:

a pressure vessel defining: (i) a working volume inside the pressure vessel, (ii) a first channel providing liquid communication through the pressure vessel to the working volume of the pressure vessel, and (iii) a second channel providing liquid communication through the pressure vessel to the working volume of the pressure vessel; and

a substantially tubular sample container defining a sample volume inside the sample container, the sample container comprising:

a first end member;

a second end member, the first and second end members configured to grip ends of a cement sample in the sample container;

walls extending from a first end with an opening to a second end with an opening, the sample container disposed in the working volume of the pressure vessel with the sample container substantially sealed to prevent liquid communication between the sample volume of the sample container and portions of the working volume of the pressure vessel outside the sample container; and

a tubular member having walls that are substantially sealed to the first end member and the second end member, the tubular member comprising a material that is more flexible than a material of the first and second end members,

wherein the sample container is positioned such that the first channel provides liquid communication through the pressure vessel to the sample volume of the sample container; and the second channel provides liquid communication through the pressure vessel to the portions of the working volume of the pressure vessel outside the sample container.

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